STANLEY F. CZAJKOWSKI and JOSEPH S. J. PERI

STRATEGIC COMMUNICATIONS NETWORK PERFORMANCE EVALUATION MODEL

The Strategic Communications Continuing Assessment Program is designed to give analytical support to the Navy in assessing the performance of radio communications systems for Navy strategic forces during all phases of a general war. As a tool for timely and technically rigorous evaluation of system performance, a computer model has been designed and implemented. This article discusses the impetus for constructing the computer model, describes its structure in some detail, and contains sample graphics output.

BACKGROUND

The United States maintains continuously alert strategic military forces equipped with strategic weapons. These forces are divided into three categories: intercontinental ballistic missiles deployed in hardened underground silos in the midwest, FB-111 and B-52 bomber aircraft on runway alert at various U.S. military airfields, and submarine-launched ballistic missiles carried on board nuclear-powered submarines operating covertly throughout the Atlantic and Pacific Oceans. Typically referred to as the Triad, these forces act as a deterrent to attack on the United States by nuclear-capable foreign countries. Ensured communications from the National Command Authority (i.e., the President and the Secretary of Defense or their duly deputized alternates or successors) to the geographically dispersed weapon platforms are essential for preserving the validity of the Triad's deterrent capability. Moreover, the communications must be able to withstand jamming and physical attack by an enemy.

Over the last 13 years, the Laboratory has provided performance assessments for the many communications systems supporting the Navy leg of the Triad. APL's analysis capabilities in this area have been substantially enhanced through the development of a computer model — the Strategic Communications Continuing Assessment Program Computer Analysis System — to evaluate quantitatively radio communications systems performance throughout the pre-, trans-, and post-attack phases of a hypothetical attack on the United States. This system is being used to assess the performance of both current and planned systems for communications with deployed (submerged) submarines.

OVERVIEW OF THE COMPUTER ANALYSIS SYSTEM

The validity and utility of a computer model of a real-world process or system depend on the model's ability to produce results that reasonably match actual observations. To achieve this capability, the model developer needs to understand the real-world system and be able to identify and express, in symbolic terms, all factors that significantly affect system behavior.

The factors that determine the performance of radio communications systems in particular can be partitioned into two groups — those related to the physical environment in which the system is designed to operate and those defining the physical and operational aspects of the communications system itself. Specifically, to provide a representation of the physical environment during a general war and its effects on radio communications, the model must be able to simulate

1. The physical and electromagnetic properties of the earth's atmosphere under benign conditions,
2. The effects on these atmospheric properties of multiple large-scale explosions at various locations and times,
3. The propagation of radio waves at various frequencies through the atmosphere under benign and disturbed conditions.

To model the communications system adequately, the following factors must be accounted for:

1. Transmitter characteristics: geographic location, power, frequency, reliability, and antenna parameters;
2. Information transfer parameters: data rate, modulation and encoding schemes, and amount of information to be transferred;
3. Receiver characteristics: geographic location, reliability, signal processing, and antenna parameters;
4. Operational parameters: transmission and reception protocols and message processing procedures.

In the computer model, the environmental and communications system parameters are handled by two main programs:

1. The Simulation of Multiple Bursts and Links (SIMBAL) program provides a representation of the physical environment and produces propagation data for communications links in terms of received signal quality as a function of time.
2. The Nåvy Strategic Communications Simulator (NSCS) simulates the flow of information through the user-defined communications network and collects statistics on the time and probability of reception at various receiving facilities.

Three other programs of the model provide input formatting, program interface, and output data processing:

1. The Simulation of Multiple Bursts and Links input processor, which reformats user-supplied data for input into the signal propagation code.
2. The Navy Strategic Communications Simulator preprocessor, which integrates the radio frequency propagation data output by the propagation program with predicted atmospheric noise characteristics in a format acceptable as input to the communications simulator;
3. The graphics post-processor, which processes and graphically displays the statistical output generated by the communications simulator.

Figure 1 shows the interrelationships of the five program modules comprising the model along with user-supplied input data files. The following paragraphs describe each module briefly. A more detailed description is contained in Ref. 1.

The Simulation of Multiple Bursts and Links Input Processor

This input processor, a 300-line PL/I program, reads three input files, combines the data from those files, and writes the information in the format required for input into the propagation module. The first input file contains the locations (latitude, longitude, and altitude) of all the facilities in the communications network to be assessed. Transmitter powers are stored in the second file. The third file contains a list of link parameters such as the names of transmitting and receiving nodes, the link frequency, and the assigned jammer.

Simulation of Multiple Bursts and Links Processing

A program was developed by Kaman Tempo to predict the performance of communications links in a disturbed atmosphere. The model can handle hundreds of communications links. The set of links may use any mix of frequencies in the very-low-frequency/low-frequency (VLF/LF) or high-frequency (HF) bands.

The code is a combination and enhancement of previously developed propagation models. Various time-consuming calculations of physical processes in these earlier models were replaced by fast numerical algorithms derived from fits to data generated by the detailed models. The modifications were designed so that the program would process large-scale communications-links problems efficiently while maintaining prediction accuracy.

The code accounts for the effects of increased ionization in and below the D-region of the ionosphere (about 20 to 100 kilometers altitude), delayed radiation from both high- and low-altitude debris sources, and prompt radiation from high-altitude detonations. For each VLF/LF communications link, the program outputs the received signal level and change in signal level as a result of ionospheric disturbance. For these links, the changes in atmospheric noise and signal-to-noise ratio can also be obtained.

Navy Strategic Communications Simulator Preprocessing

The signal propagation module produces output in a form that must be modified before it can be used by the communications simulator. The function of the preprocessor is to perform this reformatting.

The communications module expects propagation data in the form of signal-to-noise ratio. The propa-

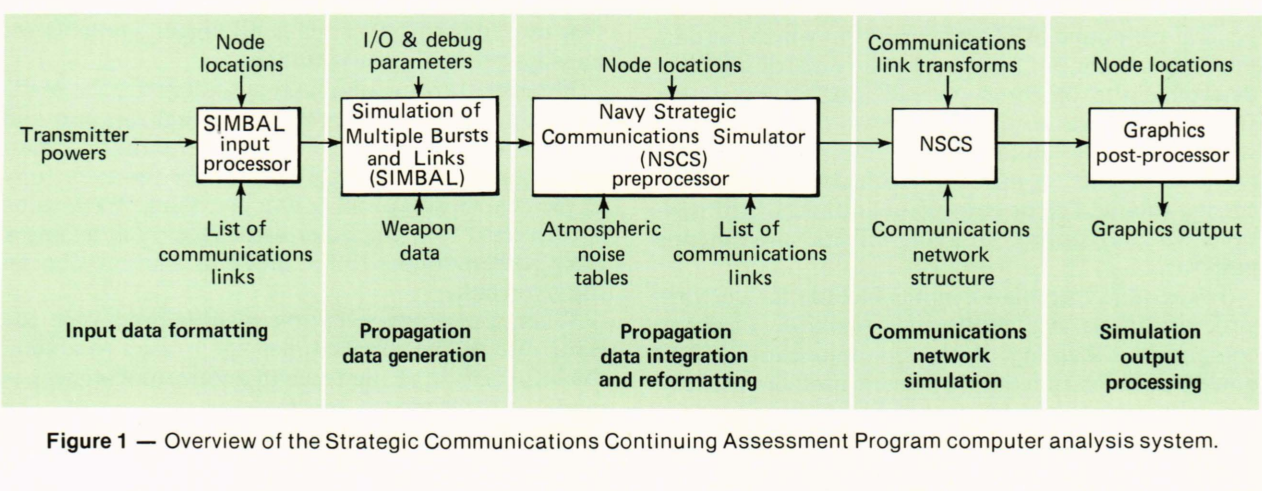

Figure 1 — Overview of the Strategic Communications Continuing Assessment Program computer analysis system.

gation program output for VLF and LF, however, is in terms of signal strength, change in signal strength, and change in signal-to-noise ratio. The preprocessor combines these data with atmospheric noise values obtained from a data base created from the International Radio Consultative Committee tables to produce the ratio values.

In the case of HF propagation, the signal prediction program supplies its own estimate of the noise strength and calculates an estimate of the signal-to-noise ratio. In the HF band, the probability that atmospheric conditions will exist for the propagation of a skywave decreases as frequency increases. To account for this phenomenon, the preprocessor computes and associates with each signal-to-noise ratio a parameter called the probability of propagation.

For all frequencies, the preprocessor associates jammers with transmission links and organizes the data so that the communications simulator will have access to signal-to-jam ratio values at the same time it accesses signal-to-noise ratio values. Furthermore, estimates of the standard deviations about these values are computed. Finally, all output takes on a common format for input to the communications simulator.

Navy Strategic Communications Simulator Processing

The communications module simulates the flow of a highly structured message called an Emergency Action Message from the National Military Command System to the Fleet Ballistic Missile Submarine forces through a communications network as defined by the user. The model uses discrete-event Monte Carlo techniques to simulate (a) the survival of network nodes (fixed communications facilities, aircraft, ships, satellites, etc.) in a nuclear attack on the system, (b) failure and repair of transmitting and receiving equipment, and (c) the quality and time of acceptance of the message at receiver platforms. "Discrete event" means that calculations are performed only at those simulation times when events occur, where the list includes such possible events as message reception at a communications facility, failure or repair of transmitting or receiving equipment, and the physical destruction of a facility. "Monte Carlo" refers to the general technique of repeated trials in which random numbers are chosen from probability distributions to determine the outcome of individual trials. Other factors that are accounted for in the simulation, which affect the ability of the communication network to deliver a message, include message processing (manual error correction and piecing of multiple message copies), jamming effects, and antenna patterns.

The required simulator inputs include the network structure, node availabilities (as functions of time), equipment reliability data, communications link quality data (as functions of time), message processing delay times, and the transmission sequences for each transmitting node.

The PL/I code making up the simulation may be viewed as a series of program modules, each representing a discrete event (e.g., receipt of message, failure of equipment). With the exception of program initialization, program control is passed from one event (program module) to another. When an event is executed, the status of units within the model (e.g., clock time, equipment failure flag, number of message copies received) is updated. Each event has logic for changing the status of units in accordance with its assigned task. Also, each event has an established procedure for scheduling the event to follow and for specifying a delay time relative to the time into the simulation. An event-by-event logic diagram is presented in Fig. 2. Included in each event box is a list of major tasks performed by that event. The arrows between event boxes delineate other events that may be scheduled while processing a given event.

For each run of the program, the user inputs a time relative to the initiation of an enemy attack on the network. That time represents the time of insertion of a message into the system by a facility of the National Military Command System. On the basis of node survivability/endurance information and equipment reliability data, random numbers are drawn to determine available nodes and failure/repair times for transmitting and receiving equipment. The resulting time-dependent status of the network is called a network realization. The message is then propagated through the network many times, while the number of messages accepted and the associated acceptance times are recorded for submarines and other nodes of interest.

During the simulated flow of a message, a list of current and future events is maintained. The events are processed in the order of increasing scheduled time, starting with the event representing the acceptance of the message by the source node of the network at the message insertion time.

If an equipment failure or repair event is processed, a flag is set to signify that the equipment is unavailable or is available for sending or receiving messages, whichever the case may be. In addition, a new event that represents the next future failure/repair time for that equipment is scheduled. When a node destruction event is processed, a flag is set so that the "destroyed" node is no longer available for message processing or jamming.

For each transmission link, a random draw is made from the appropriate predicted signal-to-noise and signal-to-jam ratio distributions at the time of message transmission to determine values for each copy of the trial message sent over a given link. Each value is converted to a character error rate by accessing a table corresponding to the mode of transmission on the given link.

When a message reception event is processed, the error rate of the received message is used to update the information at the receiving node, and a check is made to determine if the message is accepted. The chance of acceptance is based on the value of the

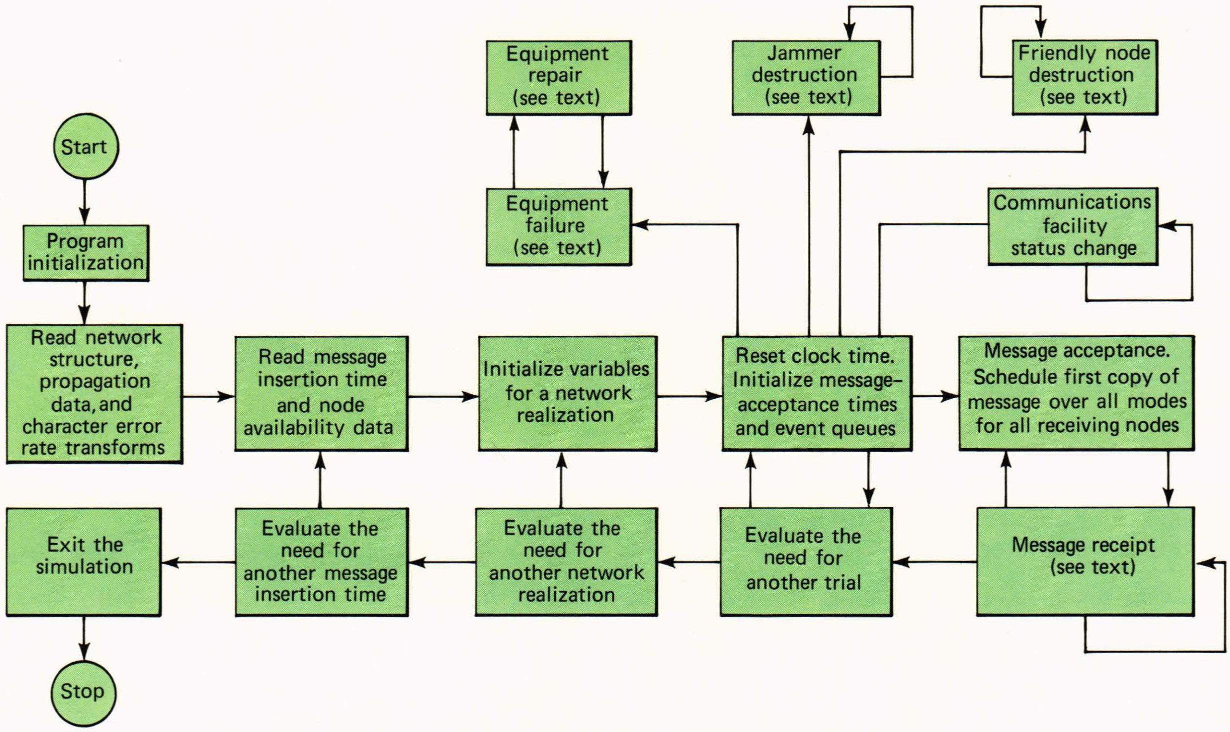

Figure 2 — Communications simulator event logic diagram.

probability of an acceptable message function, which is computed using the error rates of all received messages. This function incorporates the prescribed emergency action message validity and piecing procedures. If message acceptance does not occur, reception of the next message copy over the same link is scheduled. If acceptance does occur, a message acceptance event for that node is scheduled for the appropriate time (accounting for message processing time). When that acceptance event is processed, the accepting node begins its transmission sequence, and message receptions are scheduled for appropriate times at the listening nodes. Event processing is terminated when a time limit (specified as a model input) is exceeded.

The communications simulator produces two output files. One is a list of values of connectivity for each node that represents a submarine in the system; the other is a list of times, relative to the start of war, that each submarine accepted the message. Connectivity represents the probability that the emergency action message will be accepted by a submarine at a given location within the maximum allowable time. The values of connectivity and message acceptance time are output for each simulated submarine location, each network realization, and each message insertion time.

After each simulation run, the two output files may be off-loaded onto magnetic tape cassettes for later processing and graphical display. The tapes serve as input to the Graphics Post-Processor, a stand-alone computer graphics system that processes the taped data and generates X-Y and map contour plots on Tektronix 4054 desktop computers.

Output Graphics Processing

The post-processor accomplishes three separate processing tasks. First, its communications software is used to make log-on connection with the IBM 3033 and to receive any communications simulator output file. Second, a significant portion of the post-processor software is devoted to reduction of these data. Statistical treatment of the simulation output is provided in a format acceptable to the plotting portion of the software. Finally, the post-processor allows several plotting options on a menu select basis.

The user can display any of eight measures of end-to-end system performance. Four of these (connectivity, coverage, availability, and survivability) are hierarchical in nature and assess the ability of the communications system to achieve certain specified threshold levels of performance within a selected time period. The other four (message acceptance probability, message acceptance time, fraction of submarine operating area accepting the message, and communications commit time) assess the absolute ability of the system to deliver emergency action messages to the submarines; i.e., the measures are not relative to present thresholds.

The analyst selects the set of performance measures to be graphed. A communications simulator output tape is then used as input to the appropriate data reduction program module.

The reduced data, resident on floppy disk, may then be plotted in the format of an X-Y graph or a contour map plot. The graph selections available for the connectivity output include:

1. Connectivity distribution for any submarine location,
2. Coverage distribution,
3. Availability versus insertion time of the emergency action message.

Using the map and contour plotting routines, the connectivity values may be represented as contours over the Fleet Ballistic Missile submarine's operating area.

The contours and operating area may be displayed on any of three map projections, including a Mercator projection, an equal area projection, and a projection that represents the view as would be seen from a satellite at a specified latitude, longitude, and altitude.

The graph selections available for the message acceptance time values that are output from the communications simulator include:

1. Message acceptance probability for any submarine location,
2. Fraction of submarine operating area accepting the message,
3. Communications commit-time distribution.

The three map projections are available to display either message acceptance time or message acceptance probability over the submarine operating area.

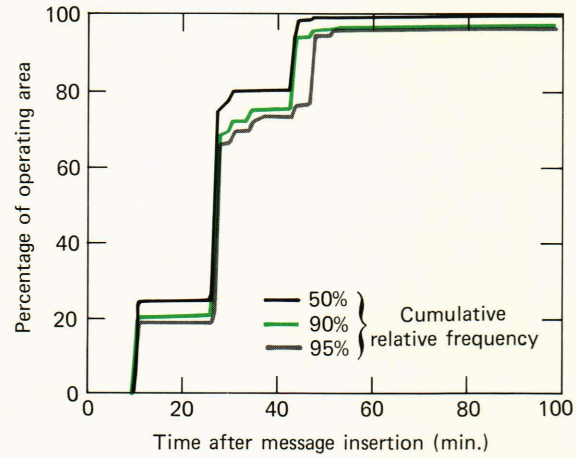

Figure 3 — Sample plot of the fraction of the submarine operating area in which message acceptance is achieved versus time after insertion of an emergency action message.

SAMPLE GRAPHICS OUTPUT

Figure 3 is a plot of the fraction of the submarine operating area in which message acceptance is achieved as a function of time after message insertion. Associated with each curve is a particular level of cumulative relative frequency. This quantity estimates the probability of equaling or exceeding the

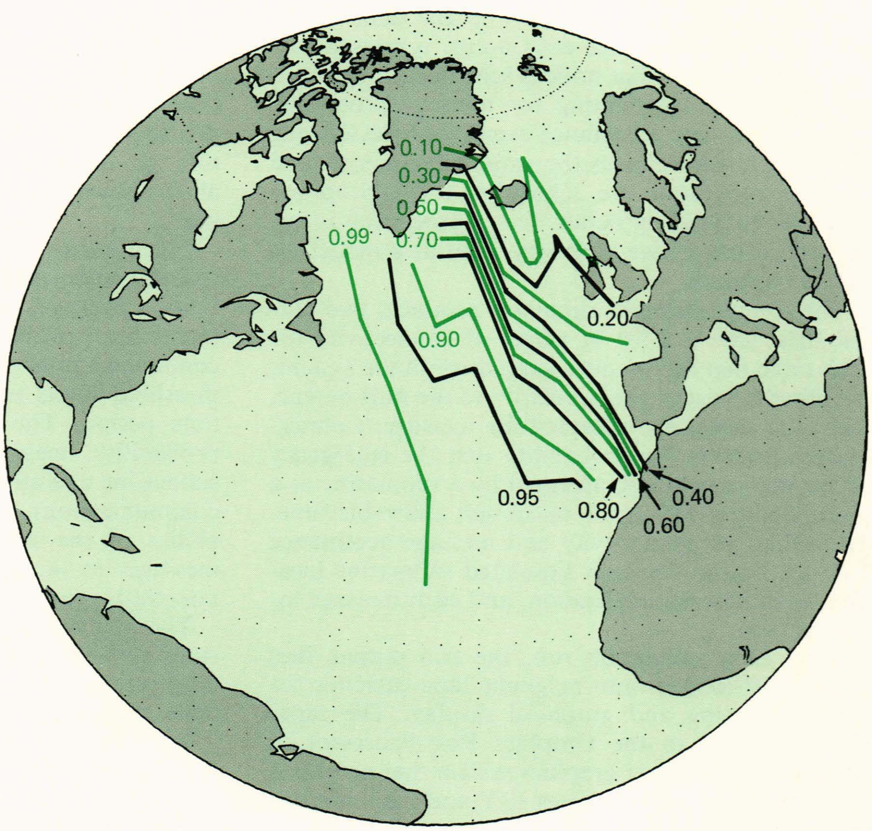

Figure 4 — Sample plot of estimated message acceptance probability for individual submarine locations as a function of time after emergency action message insertion.

value represented by the height of the curve. For the curve labeled 90%, for example, there is a 90% probability that the actual value of the fraction of operating area accepting the message will equal or exceed the height of the curve. Plots such as the one shown in Fig. 3 can be drawn for any message insertion time.

Message acceptance probability is defined as the probability that an emergency action message will be received and accepted. Its value depends on the receiving node's location, the time the message was inserted into the communications network, and the elapsed time since message insertion. The probability at any time after message insertion is estimated as the fraction of trial messages received and accepted at the given location by that time.

The message acceptance probability data for a particular message insertion time can be graphed for individual submarine locations as a function of time after message insertion or for all locations and a particular time after message insertion as in Fig. 4. The satellite-view projection was used in graphing this figure. A sequence of the geographic plots can be generated for various times after message insertion.

CONCLUDING REMARKS

The Strategic Communications Continuing Assessment Program computer analysis system was constructed and implemented when it became the Navy's desire to assess quantitatively the performance of the U.S. Strategic Communications System. Full operational capability was available in the spring of 1981. Since that time, the system has served as a powerful computer tool for assessing the performance of current and future strategic communications systems in a disturbed environment. Performance assessments to date have ranged from predicting enhancements of overall system performance as a result of additions of major communication systems to studying modifications in operational procedures. For example, the assessment work has determined the performance of the U.S. Strategic Communications System under various attack scenarios, optimal operating areas for a Navy communications relay aircraft, the performance of new systems such as a transportable VLF system, the performance of new transmission modes for existing systems, and the effect of rough seas on the reception of messages by submerged submarines. The results of these assessments have aided the Navy in determining both technical and operational methods to improve wartime strategic communications to submarines.

REFERENCE

[1] P. M. Thompson and S. F. Czajkowski, *SCAP Computer Analysis System Specification*, JHU/APL FS-82-050 (Mar 1982).